Towards Detecting Signatures of Life with the Future LIFE Telescope

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LIFE can accurately constrain the size and surface conditions of an Earth-twin exoplanet.

LIFE can detect the biosignature pair O_3–CH_4 in an Earth-twin exoplanet.

Introduction – Earth-Twin Study

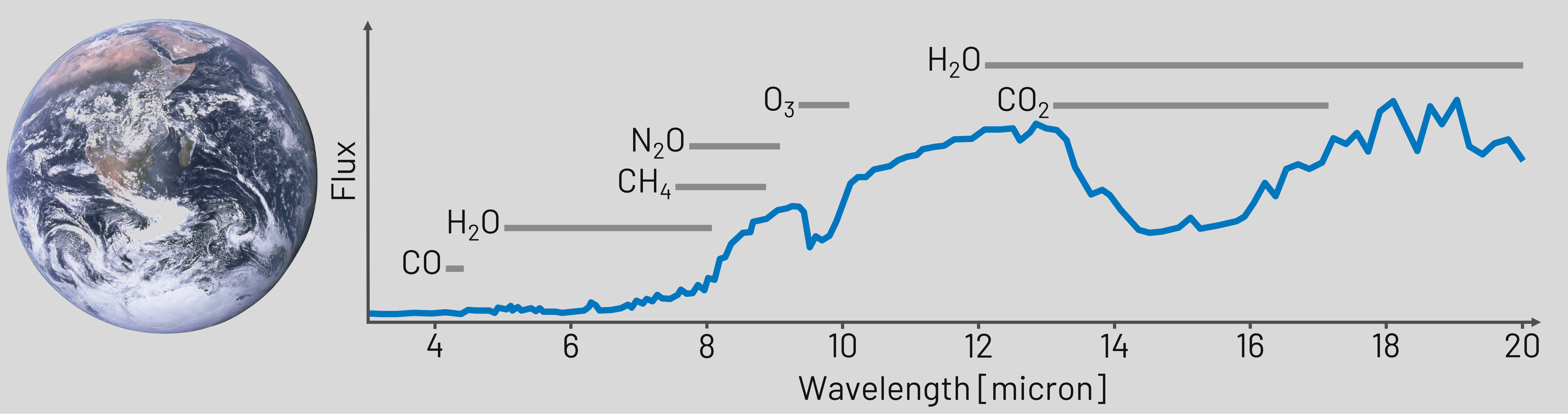
The goal for LIFE is to correctly characterize the atmospheres of rocky exoplanets and potentially detect biosignature pairs (e.g. O_3–N_2O or O_3–CH_4) in the mid-infrared (MIR). It is crucial to investigate how accurately the exoplanet's MIR thermal emission needs to be measured to allow for a sufficiently precise characterization.

To find a first answer to this question, we studied the **MIR emission of a cloud-free Earth-twin planet** orbiting a Sun-like star at a distance of 10 pc from us (Fig. 1). With the LIFEsim instrument simulator [2], we

Konrad+, 2022 [1]

estimated the wavelength-dependent noise expected in observations with LIFE by accounting for all major sources of astrophysical noise. We then ran atmospheric retrievals for **spectra of different quality** (variable resolution (R) and signal-to-noise ratio (S/N)), to analyze how well we manage to characterize the Earth-twin atmosphere as a function of the quality of the thermal emission spectrum. This approach provided us with **first estimates for the minimal requirements for the LIFE instrument.**

Figure 1: Simulated MIR Earth spectrum. We indicate the most relevant absorption bands of all considered atmospheric gases.

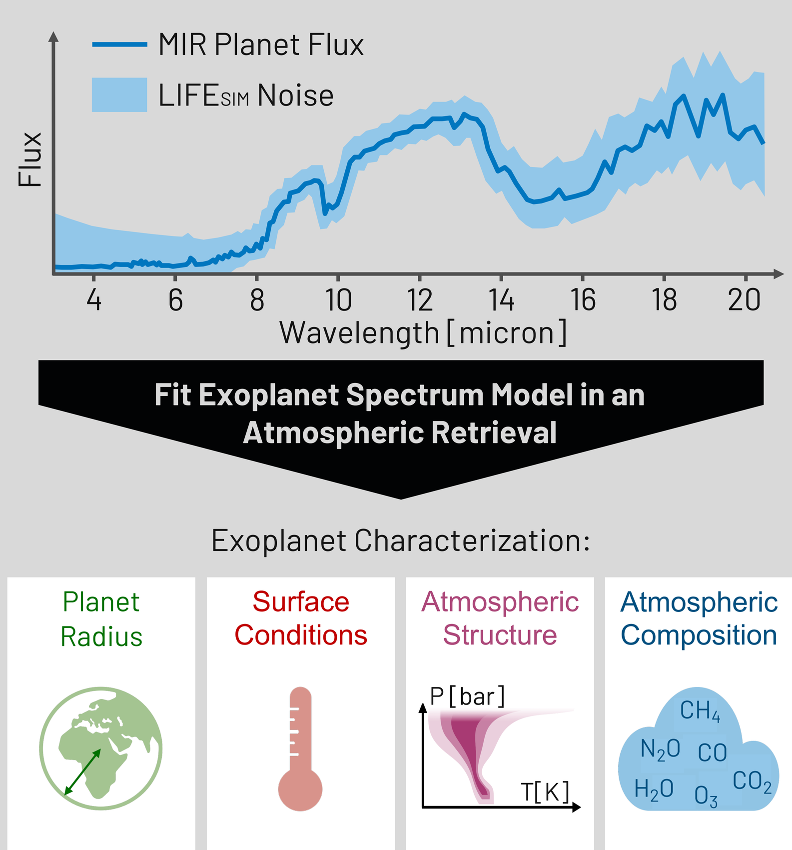


Background – Atmospheric Retrievals

A **retrieval** finds the best fit of a model for the exoplanet spectrum to an observed spectrum. Further, it retrieves Bayesian **estimates and uncertainties for the model parameters** (Fig. 4). The parameters describe planet and atmosphere properties, such as the planet radius, the pressure-temperature structure, and the abundances of atmospheric molecules. Our retrieval code depends on two subroutines:

1. **petitRADTRANS [3]:** 1D radiative transfer routine that calculates the spectrum for a given set of model parameter values.
2. **MultiNest via pyMultiNest [4,5]:** Parameter estimation with Nested Sampling [6]. Finds the set of parameters (with uncertainties) that best fits the observed spectrum.

Figure 4: Retrieval procedure. By running a retrieval on an observed exoplanet spectrum we can infer planetary and atmospheric properties and characterize the exoplanet.



Background – Biosignature Pairs

Biosignatures are substances, objects, or patterns that, if detected, strongly suggest biological activity. **Atmospheric biosignatures** are gases that are either produced directly via biological processes (e.g. O_2, CH_4, N_2O), or are derived from the latter via environmental effects (e.g. O_3 from O_2 via photochemistry). However, since most biosignature gases could also be produced in abiotic processes, the detection of a single gas is not a robust biosignature. But the simultaneous presence of two gases with abundances out of thermodynamic equilibrium (e.g., for Earth, O_2/O_3 with CH_4 or N_2O) can only be justified if both gases are continually replenished by biological processes. These pairs of gases are called **biosignature pairs** [7, 8].

Figure 2: Retrieval results for the planetary radius R_{pl}, surface pressure P_0, and surface temperature T_0 for different R and S/N of the LIFEsim spectra. The error bars denote the 68% confidence intervals.

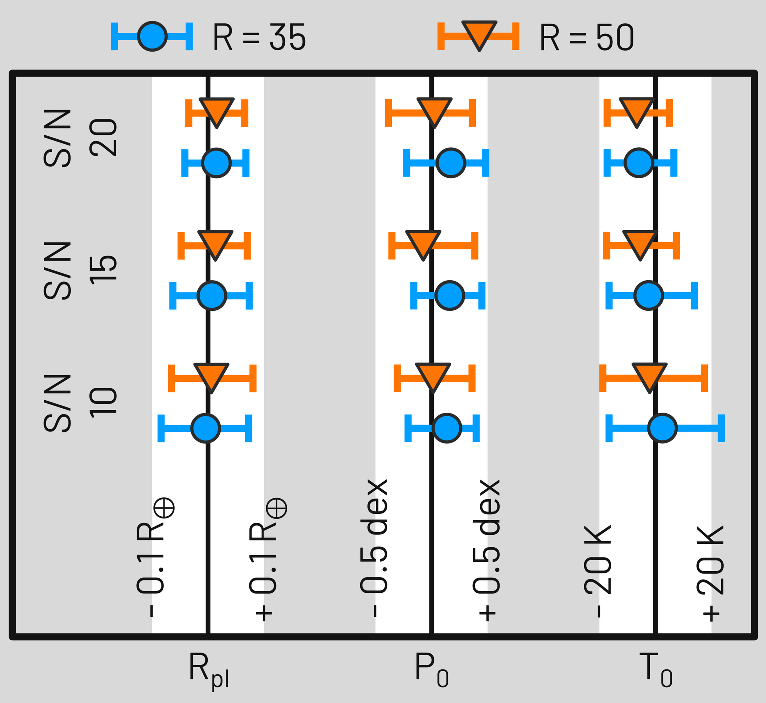


Figure 3: Retrieval results for trace gases at different R and S/N LIFE mock observations. ✓: Constrained abundance (uncertainty < ± 1.0 dex); −: constrained but cannot exclude lower abundances; ✗: unconstrained abundance.

Result & Conclusion – Earth-Twin Study

Independent of the spectral quality, the planet **size and the surface conditions are well constrained**. For all tested MIR LIFEsim spectra we manage to constrain (Fig. 2):

- **Planet radius:** uncertainty < ± 0.1 $R_\oplus$
- **Surface temperature:** uncertainty < ± 20 K
- **Surface pressure:** uncertainty < ± 0.5 dex

The uncertainties on the retrieved values decrease slightly with increasing quality of the considered spectrum.

The retrieval **results for the main molecules** present in Earth's atmosphere show the following behaviour (Fig. 3):

1. **CO_2, H_2O and O_3:** Detectable independent of the spectral quality. The uncertainty on the retrieved abundance is < 1.0 dex and decreases with increasing spectral quality.
2. **N_2O and CO:** Not constrained for any of the tested spectra. Their MIR features are small relative to the LIFEsim noise. Therefore, the **O_2/O_3–N_2O biosignature is not detectable** for an Earth-twin.
3. **CH_4:** Outcome depends on spectral quality. Further analysis shows that a spectrum of R ≥ 50, S/N ≥ 10 is required to detect CH_4 in an Earth-twin exoplanet. This would make the **O_2/O_3–CH_4 biosignature accessible**.

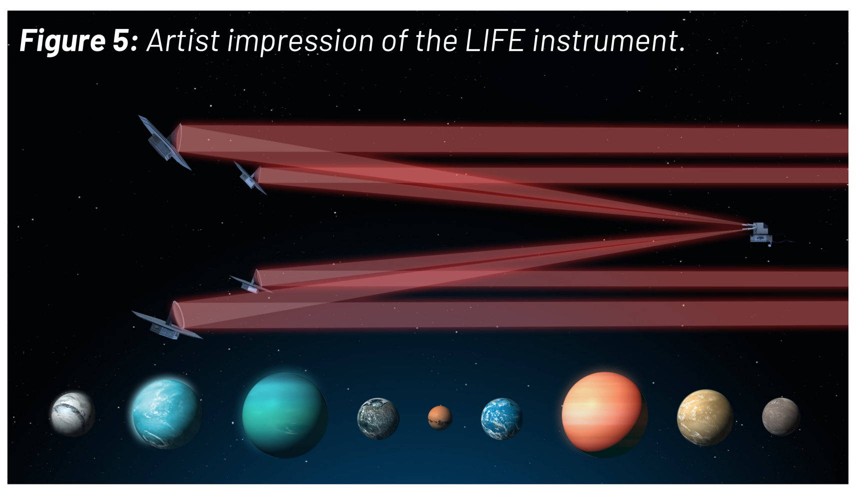
The abundances of Earth's main atmospheric gases **N_2 and O_2** (not in Figure) are not constrainable, because they have no significant spectral features in the MIR. However, we can **infer a ≈ 1 bar thick atmosphere**, of which the bulk is transparent in the MIR.

Background – LIFE

A long-term goal for exoplanet research is to assess the habitability of Earth-like exoplanets, characterize their atmospheres, and search for signs of life. For this, **a new generation of space-based telescopes** is required. NASA aims to measure the stellar light reflected by exoplanets in the visible (VIS) and near-infrared (NIR) [9,10]. In contrast, the **"Large interferometer For Exoplanets" (LIFE)** [11] will measure the MIR thermal emission of terrestrial exoplanets. The LIFE collaboration is working toward realizing such a mission (see also talk by Eleonora Alei in Session 7; Fig. 5).

A planet's MIR emission is of interest to us, because many important molecules have detectable spectral features in the MIR but not in the NIR/VIS (e.g. CH_4). Further, the MIR allows for a better assessment of the planetary radius, lower atmosphere, and surface conditions (if cloud-free) [12, 13]. Finally, the MIR provides direct access to the potential biosignature pairs O_3–N_2O and O_3–CH_4 (O_3, N_2O, and CH_4 all have spectral features in the MIR range).

Figure 5: Artist impression of the LIFE instrument.



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